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13. ABSTRACT *(Maximum 200 words)*

The following document reviews advances in the optoelectronic areas supported by the contract. Specifically, monolithic integration of Vertical Cavity Surface Emitting Lasers (VCSELs) arrays with Heterojunction Bipolar Transistors (HBTs) is described for the realization of smart pixels. Latching, non-latching and bistable switching is demonstrated for the arrays. In addition, it is shown that the arrays can perform cascadable Boolean logic. Further, low series resistance and high speed(> 9 GHz) VCSELs were realized while maintaining average output powers of 2-5 mW. Pico-second pulse generation in diode lasers-both edge emitters and VCSELs is reported, and regenerative mode-locking is described for both types of device. Optical pumping of RPG-VCSEL structures is described, and the approaches to phase coupled VCSEL arrays is enumerated. Finally, preliminary experiments and models aimed at the understanding of dynamic behavior in VCSELs are presented.

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VERTICAL-CAVITY SURFACE-EMITTING LASERS AND VCSEL-BASED OPTICAL SWITCHES FOR PARALLEL OPTICAL PROCESSING

Statement of Program Objectives

Two-dimensional, surface-normal arrays of optical switches can perform a variety of data processing functions including optical detection and regeneration, switching and routing, logic and storage. These "smart pixel" arrays can be optically cascaded to form very-compact, very-high-information-throughput, parallel processing systems. The objective of this research program is to develop a novel monolithic optoelectronic technology for the two-dimensional parallel processing of optical data. The technology consists of a family of optically cascadable, high speed optical and optoelectronic switches based on the monolithic integration of AlGaAs/GaAs vertical-cavity surface-emitting lasers (VCSELs), heterojunction phototransistors (HPTs) and photothyristors (PNPNs), which can perform all of the aforementioned functions. As a prerequisite for this switching technology, an important goal of the program is to develop high performance surface emitting lasers with good electrical and optical characteristics -- including low operating currents and voltages, low power dissipation, a broad operating temperature range, high power efficiency, high speed, and good modal properties.

Technical Problems

Optical processing offers many important advantages, including parallelism, high density, compactness, no electrical loading, and reduced timing skew. Unlike electrical signals, the reconfiguration and manipulation of light beams are not easily achieved, requiring even in simple cases a prohibitive amount of optical hardware and precise optical alignment. To minimize these problems, we seek a more flexible optoelectronic approach using monolithic arrays of multi-functional, self-emissive (rather than reflective) optical devices that provide parallelism and are simpler and more compact than conventional optoelectronic integrated circuits (OEICs), while minimizing the optical routing that dominates the pure photonic switching approach. Optical switches based on the integration of VCSELs with HPTs or PNPNs are simple devices that can be optically or electrically switched, while providing electronic and optical gain, switching, and logic without any other electronic intermediary or external ooptical source or bias beam.

A major problem for dense arrays is the power dissipation of each device, which needs to be reduced to an acceptably low level (<10 mW per device). Although the VCSEL is a microcavity

laser with low operating currents, the achievement of low power dissipation and a high power efficiency have been hampered by its large series resistance and high operating voltage. The resulting self-heating exacerbates the misalignment of the gain peak with respect to its cavity mode, which promotes thermal run-away and severely limits its output power and operating temperature range. These characteristics must be improved before efficient optical switches can be made.

The development of efficient, functionally flexible, VCSEL-based optical switches also required the co-development of HPTs with a large optical gain-bandwidth product, and PNPN switches with both high gain and strong positive feedback. Thus our effort was also focused on the development and optimization of each these component technologies, in addition to the VCSEL.

General Methodology

The aim of this program is to create a new switching technology that monolithically integrates several discrete components, including the VCSEL, the HPT, and the photothyristor. Each of these requires individual efforts in device design, epitaxial growth, and process development, while their monolithic integration requires additional efforts in the design of a compatible epilayer structure and specialized processing techniques. Every stage, from epilayer to device to circuit, involves its own modeling and characterization. The optical and electrical characteristics of the VCSEL, HPT, and PNPN have been modeled, and an optimal device structure for each has been developed. These devices were grown by both molecular beam epitaxy (MBE) and organometallic vapor phase epitaxy (MOCVD), and the material was characterized using photoreflectance spectroscopy, photoluminescence, and optical pumping techniques, which are critical to their proper performance. In addition to the standard microfabrication tools, specialized processes such as ion implantation and chemically-assisted ion beam etching (CAIBE) were also used. Device characterization included all the standard dc and pulsed electrical (current-voltage, capacitance-voltage) and optical (light-current) techniques, plus additional characterization of their high and low temperature characteristics (90K to 600K), spectral and modal properties, and high frequency modulation response.

Technical Results

High Performance Vertical-Cavity Surface-Emitting Lasers

VCSELS with Low Series Resistance and Good Electrical Characteristics

The room temperature, cw operation of top-surface-emitting VCSELs with high output power is limited by their high series resistance and high threshold voltage, which increase the electrical power dissipation and limit their output optical power, efficiency, and operating temperature range. The high series resistance arises from a combination of contact resistance, spreading resistance, and the impedance of the energy barrier at each heterointerface to carrier transport. The interfacial resistance can be reduced by a variety of different grading techniques. Using a continuous linear grading of the heterointerfaces, we have shown the series resistance can be

significantly reduced to a low level. High quality VCSELs with continuous compositional grading have achieved excellent room-temperature, cw characteristics, including high output power (5 mW for 16 μm devices), low threshold current (<2 mA) and voltage (<1.8V), high slope efficiency (up to 80%), low series resistance (20 W) and high power efficiency (8%). The series resistance, varying from 65W for a 5 mm diameter device to 20W for a 40 mm device, are the lowest values ever achieved. Power dissipation level as low as 10 mW per device has also been demonstrated.

Modeling of the Heteorinterfaces and the VCSEL'S Electrical Characteristics

Theoretical studies were carried out to model the electrical transport properties of the hetero-interfaces for different grading schemes and doping levels. True ohmic behavior was found to exist only when these interfaces have multi-step or continuous grading, and only when the doping levels are sufficiently high. A current spreading model was formulated, from which the various contributions to the VCSEL's series resistance were calculated, showing excellent agreement with our experimental data. These studies led to state-of-the-art VCSELs with the lowest series resistance, plus peak operating voltages that are typically below 2.5V.

VCSELs with a Very Wide CW and Pulsed Operating Temperature Range:

By optimizing the alignment of the lasing mode with the gain peak for a suitably chosen operating temperature range, and by reducing the thermal dissipation, VCSELs with a very wide temperature range for dc and pulsed operation have been achieved. We have demonstrated cw operation over a wide range of temperatures from 90^{o}K to >400^{o}K (1mW optical output at 400^{o}K), and pulsed operation from 90^{o}K to >560^{o}K, which are state-of-the-art results. The effects of mode misalignment on such factors as the threshold current and quantum efficiency have been studied, from which the optimal room-temperature detuning was selected for the high temperature operation.

High Speed Modulation and Modeling of VCSELS

With a view to using the VCSEL as a high speed source for multi-gigabit data links and optical networks, we have optimized its high-speed performance through device and package design, achieving a small-signal modulation bandwidth of >9GHz, and a large amplitude response (to pseudorandom modulation at 1 Gb/s) with a rise time of ≅60 ps. The electrical impedance of packaged VCSELs was modeled using S-parameter analysis, providing an equivalent circuit that includes both intrinsic and extrinsic effects. The VCSEL's optical modulation response was also measured and modeled, and projections of its intrinsic modulation bandwidth have been made.

Design, Fabrication and Demonstration of a Versatile New Family of VCSEL-Based Optical Switches

Different optical processing applications call for switches with different functional characteristics, including either latching or non-latching behavior, and with either electrical or optical control of switching. We have developed a versatile new family of high performance, cascadable optical switches based on a single epilayer design that permits the integration of a non-latching HPT/VCSEL switch, a latching PNPN/VCSEL switch, and an optically bistable PNPN/VCSEL switch, all on a single substrate.

Latching PNPN/VCSEL Optical Switch

The PNPN/VCSEL switch integrates a VCSEL with a photothyrsitor (PNPN), from which it derives its latching characteristics. The PNPN exhibits bistable resistive and conductive states, separated by a switching voltage V_S that is reduced by illumination. The PNPN is biased in its resistance state in the dark, and switching to the conductive state is effected by applying an optical pulse of sufficient intensity to reduce V_S to the bias voltage level, which switches on the photothyristor that in turn drives the VCSEL above threshold. Due to the strong positive feedback inherent in the thyristor structure, an optical power as low as 10 nW is able to effect switching. Switching occurs abruptly at a threshold of 15 nW, and produces a VCSEL output power of 1.3 mW. An optical gain of 30,000-100,000 has been achieved. The output power remains latched (memory) even after the optical input is removed, as long as the bias voltage remains above threshold. The dc power dissipation of the switch is about 15 mW. In the presence of strong positive feedback, the optical contrast is much greater than 30 dB, and switching energy of 5 pJ has been measured.

Non-Latching HPT/VCSEL Switch

By removing the two uppermost p-layers of the thyristor, the monolithic PNPN/VCSEL switch becomes an HPT/VCSEL switch, which exhibits non-latching, threshold switching characteristics, providing optical amplification but no optical storage capability. Switching occurs when the optically-injected photocurrent is amplified by the gain of the HPT to a level that is sufficient to drive the VCSEL above threshold, from which the switch derives its threshold characteristic. The optical power required to effect switching (28 mW) is larger than that of the PNPN/VCSEL switch, due to the absence of any positive feedback. The power dissipation of each switch depends on the efficiency of the VCSEL as well as the gain of the HPT, and a value less than 12.5 mW has been demonstrated. The switching speed depends on the HPT(<3 ns) rather than the VCSEL (≅60 ps).

Bistable PNPN/VCSEL Switch

A bistable optical switch with characteristics intermediate between those of the PNPN/VCSEL switch and the HPT/VCSEL switch has been achieved by modifying the amount of positive feedback in the former. Between the resistive and conductive states in the electrical characteristics of a photothyristor lies a bistable region bounded above by the holding current I_h of the switch, which is a function of the input optical power, and is a measure of the strength of

the optical feedback. For switching to occur between bistable states and in order to turn on the VCSEL, I_h must be increased to several mAs. This is achieved by reducing the positive feedback in the PNPN with a shallow proton implant. The bistable optical transfer characteristics of the switch makes it possible to control switching and latching optically. The switch turns on abruptly at input intensity of 47 mW, producing an optical output of 1.1 mW, and it remains at this level until P_{in} falls below an optical holding level of 16 mW. The peak optical gain is about 23, and the optical contrast is about 30 dB. This is the first demonstration of bistable optical switching in a VCSEL-based switching device, and its operating principles have been theoretically modeled and numerically simulated.

VCSEL-Based Cascadable Boolean Optical Logic

Simple Boolean logic functions, such as AND, OR, NAND, NOR, INVERT, or XOR can be implemented optically in a single stage using any of the three types of threshold switches. The integrability of the different logic functions on a common substrate is beneficial for the implementation of more complex logic functions that may be carried out in parallel. Latching AND and OR optical logic gates have been demonstrated using the PNPN/VCSEL switch. Optical INVERSION has been achieved by connecting the PNPN and VCSEL in parallel, and the combination in series with an external resistor. The dc power dissipation of this gate is 12.5 mW. Optical NAND and NOR gates have been demonstrated using the INVERTER geometry. A single-stage non-latching XOR gate has also been demonstrated using a novel geometry in which pairs of HPTs and VCSELs are interconnected in a symmetrical configuration.

Important Findings and Conclusions

Substantial progress has been made in designing VCSELs with very good cw characteristics, especially a low series resistance and threshold voltage. VCSELs have also been optimized for high temperature cw performance, with a very broad operating temperature range. High speed performance has been achieved under both small and large signal modulation conditions. It remains an outstanding challenge to improve the thickness uniformity of epitaxially grown VCSEL structures from ±2% to <±1%, in order to minimize the modal misalignment to the gain peak. It is also necessary to further reduce the power dissipation.

A family of high performance, multi-functional optical switches have been achieved with a great deal of functional flexibility and versatility. Optical switching, logic, amplification, and storage have all been demonstrated. Here, as for the VCSELs themselves, power dissipation is an unresolved issue. The switching speed as well as switching energy can be further improved from their current respectable levels.

Significant Hardware Development

A variety of different optoelectronic component technologies, including the VCSEL, the HPT, and the photothyristor have been demonstrated. Monolithic switches integrating these functional

groups have also been achieved in the forms of non-latching HPT/VCSEL switches, and latching or bistable PNPN/VCSEL switches. Optical logic gates based on these switches have also been demonstrated.

Implications for Further Research

Substantial progress has been made in developing and understanding the VCSEL and the VCSEL-based optical switching technology, as evidenced by the improvements in device performance. Novel devices have also been demonstrated that may potentially facilitate the unification of the logic, interconnection, and electronic control functions, i.e. to realize the smart pixel. Future work should be guided by a *minimalist* approach, with the view towards reducing the component count, size, cost, and complexity.

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PICOSECOND PULSE OF SEMICONDUCTOR LASER

Technical Problems

Stable sources of picosecond pulse lasers have numerous applications in optical communications, optical control and measurement of high-speed integrated circuits and devices, and optical clock distribution in high speed digital processors. There are different methods to gain picosecond laser pulses successfully, but a compact and robust pulse source of lasers is still the request of industry and commercial market. Especially Strong need for the laser pulse sources with continuously tunable repetition rate in the range from megahertz to a few GHz.

It is well known that very short pulse can be obtained from mode-locked lasers, but adjustment of their repetition rates is usually very cumbersome because the cavity length needs to be adjusted and the alignment of the cavity should maintain. One of best methods for generating optical pulses with tunable repetition rates is that of gain-switching semiconductor lasers. However, the usual way of gain switching technique requires highly stable RF oscillators and pulse forming elements such as step recovery diodes or comb generators which make gain switching relatively complicated for the repetition rate tuning over megahertz to GHz.

The effort was focused on the development of novel technique for the picosecond pulse semiconductor laser requiring only relatively simple off-the-shelf electronic components.

Novel Methodology

The novel technology is developed based on the regenerative feedback schemes. The broadband intensity noise of the output of semiconductor laser is accepted by a high speed photodetector and converted to the photocurrent. The preamplified photocurrent is then filtered by a narrow bandpass filter, further amplified and at last fed back to drive laser pump current. This electro-optical feedback loop is used for two different schema: (1) regenerative gain switching and (2) regenerative mode-locking.

In (1) this electro-optical feedback loop creates a strong nonlinear process in the laser medium differ from other gain-switching process. The repetition rate of the laser pulse is determined by the center frequency of the filter, therefore is easy to be tuned in a large range. In principle this range can be from DC to several GHz limited by the bandpass of carrier-photon interaction in the medium. The laser and electronics can be included in a compact, economic equipment. Any standard laser diodes with sufficient modulation bandwidth can be used for this technique.

In (2) this electro-optical loop combined with an external cavity which provides a pure optical feedback drives the laser operating in pulse. The center frequency of the filter should be equal to the reciprocal of the round-trip time of the external cavity and then determine the repetition rate of the pulse. Comparing with the usual active mode-locking technique the difficult matching problem between active modulation frequency and passive cavity length can be solved easily:

electrical modulation signal is created by optical output, matching is automatically reached, therefore the highly stable RF signal generator and extremely stabilized cavity are avoid for stable operation. If a grating is used in the external cavity, wavelength tuning can be obtained.

Main Results

Regenerative Gain Switching:

Several semiconductor diode lasers from different sources, including those made in-house (at CHTM), have been gain switched using the regenerative gain switching technique. Pulsewidths are as short as 35ps have been obtained. The amplitude of these pulses could be varied by varying the DC bias level and regenerative loop gain. Preliminary measurements indicate excellent amplitude and phase stability of the pulse train, and the pulse repetition rate was easily tuned from 240 to 430 MHz in a highly controllable manner by using a tunable RF bandpass filter. This tuning range was limited only by the choice of components available for these first experiments. With use of relatively standard components, a range of repetition rate from less than 100 Hz to over 1 GHz with any laser diode having sufficient modulation bandwidth is expected.

Regenerative Mode-Locking:

Many commercially available semiconductor lasers have been mode locked using the regenerated mode-locking technique. With a Hitachi laser diode and an external cavity length of 30 cm a stable train of pulses of ~10 ps duration is obtained. An rms timing jitters of less than 1ps is demonstrated. Easily wavelength tunability of >25nm is also demonstrated.

Vertical Cavity Surface Emitting Lasers (VCSEL)

Under the project of VCSEL several branches of research have been done. They will be described separately.

Diode Laser Pumped High Power InGaAs/GaAs RPG-VCSEL Lasers at 918 nm

Technical Problems

The problem of two-way communications between a high altitude aircraft and a submarine poses the needs of special laser performance requirements. Lasers for this application should have an output power of several joules, a pulse width of ~ms and repetition rate of ~100Hz. The high efficiency, extremely long-life, good beam quality and single frequency with narrow bandwidth are required.

Using an optical pumped VCSEL as the source of infrared radiation to be frequency doubled for transmission through the ocean can be selected to achieve this purpose, especially using a diode

laser pumped VCSEL would be required for a compact system and less expense than a solid-state laser with laser diode arrays. The low threshold and high differential gain are therefore highly required. This project is to design and fabricate a novel optically pumped VCSEL with RPG structure at 918nm wavelength and produce a good beam performance.

General Methodology

Strained-layer structure will be used in this newly designed RPG-VCSEL by employing AlGaAs/InGaAs material system. Since laser diodes will be used as the pumping sources, some special considerations must be included in the laser structure, such as absorption layer, bottom mirror reflectivity, etc. Combining several fundamental laser equations, an optimal cavity design has been proposed and it is expected this VCSEL design will have much lower pumping threshold density and high output power. To increase the total conversion efficiency, a specially designed double bottom DBR mirror is suggested and will be incorporated into the structure.

Technical Results

(i) The current VCSEL wafers with multi-quantum well structure at 850 nm (MOCVD grown) have been tested. The threshold density is measured as 67-79 kW/cm^2. The differential efficiency is as high as 25-35%. The laser emission with a spectral width of ~0.3-0.7nm (3dB) is observed. The wavelength shift as the function of temperature is measured as ~0.12nm/°C. The nonuniformity of the wafer was also studied.

(ii) A software for the designing of optically pumped VCSEL has been developed and new designed VCSEL wafer is in fabricating processing. Threshold power density as low as 10 ~ 20 kW/cm^2 is expected, which will facilitate the diode laser pumping. By integrating the laser diode with RPG-VCSEL, a compact and robust coherent optical source will be fabricated with high output power.

Fundamental study on Electrically Pumped VCSEL

Technical Problems

Electrically pumped vertical cavity surface emitting lasers are rapidly attracting current interesting for many applications. Their unique geometry and packing density provides the possibility for one- and two-dimensional array applications such as spatial light modulations, displays, and light source for digital interconnects and data links. A lot of effort is being made to improve the design of VCSEL for better performance.

This project is looking for new applications of VCSELs which will be based on the fundamental study of the characteristics of VCSELs, mainly in two direction: bistability or multistability of transverse modes which will be very useful for pattern recognition and optical communications; and VCSEL as high power source by injection locking of originally uncoupled VCSEL array into coupled in phase operation.

Technical Results:

Primary experimental observation showed new aspects of VCSEL:
(i) VCSEL can lase with two orthogonal polarization emissions, their polarization axises coincident with crystal orientation <011> and <011'>. These two polarization emissions are not coherent, have different pattern, can be switched from one to another polarization by using an external injection signal under certain conditions.
(ii) VCSELs with window size larger than 10 mm show variety of spatial pattern. Regardless the form of the gain confinement (some VCSELs have circular implant and window form, some rectangular) the VCSELs under high pump rate show both cylindrical symmetry and also rectangular symmetry. One high order transverse mode sometimes includes several nearly frequency degenerated modes with different patterns, this implies the possibility of bistability and multistability in VCSELs based on their transverse modes.

Injection phase locking of a single VCSEL device has been performed. The locking range was measured as ~ 2Å with ~1mW injection power outside the VCSEL. From the asymmetry of the locking range the linewidth enhancement factor a was obtained as 2.3. The primary experiment shows that the transverse pattern and polarization characteristics could be controlled by external injection signal in certain level. These experimental results provides the base of injection locking VCSEL arrays.

Both experiments of observation of transverse modes and injection locking of VCSEL expose variety of dynamics of VCSELs, therefore they will accelerate the fundamental study of microcavity lasers and may open new applications of them.

Further Research Program

Further Research work will be in the following directions:
(i) continuously searching bistability and multistability in VCSEL transverse modes;
(ii) injection locking VCSEL array by using phase conjugated crystal;
(iii) further study of transverse modes of VCSEL and polarization characteristics of VCSEL with the purpose to find out a way to control them.
The planed program will not be only experimental work. The theoretical modeling and numerical simulation will also be done with the collaboration with the theoretical groups.

Phase Coupled VCSEL Array (collaborated with AT&T Bell Labs Solid State Technology Center)

Technical Problems

VCSEL arrays offer great potential for use as high intensity light sources for optical communications applications as well as optical interconnects due to their scalability in 2-

Dimensions. The short cavity length of a VCSEL enables a single longitudinal mode emission. Control of higher order transverse modes is difficult to realize in large area devices which have potential to achieve higher powers. Since the output power of the laser is proportional to the active area, many different array configurations have been employed to tailor a supermode with idea Gaussian like single mode beam, and increase the potential for much greater output power with the larger active area. A broad area VCSEL with a metal grid contact over the exit aperture is therefore suggested.

Device Design

The array is formed by applying a metal grid contact on the aperture of a top surface emitting broad area GaAs/AlGaAs VCSEL which is grown by MBE in AT&T Bell lab.
The grid contact promotes good current injection through the top annealed p-ohmic metallization, while also modulating the gain and reflectivity to enhance control of the lateral modes and prevent incoherent filamentation.

Results

Different window size and grid design are tested to select optimal design for the in phase emission of single lobe. Our study shows that small window size and circular aperture could be contributing to the in phase mode selection.

A phase coupled array with a gain guide diameter of 40 mm and the window covered by a metal grid of 2 mm wide and spaced by 7 mm is tested. Using 100ns injected pulse at 10 kHz, the VCSEL array has threshold of 42.5mA and 30mW of power at 100mA. The quantum efficiency is 56%. The 2.5° divergence of the in phase far field mode is observed with drive current up to 1.2 times threshold. An increase in the drive current does not introduce new modes, although the divergence angle does increase, in conjunction with the spectral linewidth (FWHM) which increases from 2Å at 1.2 I_{th} to 4Å at 2.4 I_{th}. In opposite the VCSEL arrays with the window of 78 mm and 100 mm prefer lasing with out of phase mode. For increasing pump current further, higher order supermode are excited.

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HIGH-SPEED OPTOELECTRONICS

Task Objectives

Development of reliable (i.e. turn-key) and versatile schemes for stable picosecond optical pulse generation using commercially available diode lasers.

Technical problems

There exists a strong need for stable sources of picosecond laser pulses whose repetition rate is continuously tunable in the range of MHz to GHz. One of the best methods for generating ultrashort optical pulses at continuously tunable repetition rates is gain-switching semiconductor lasers. However it requires highly stable RF oscillators, and pulse forming elements such as step recovery diodes or comb generators, making it relatively complicated if repetition rates need to be tuned over the MHz to GHz range.

Although very short pulses can quite readily be obtained from mode-locked lasers, adjustment of their repetition rates (especially over large frequency ranges) is usually very cumbersome, partly because of the constraints imposed on the cavity lengths by the technique of mode-locking, and partly because of the need to keep the optical cavity aligned while varying the cavity length.

General Methodology

Experimental work, based on principles described below.

Regenerative Gain Switching (RGS)

Figure 1 shows the schematic of a gain-switched diode laser system, in which the modulation is derived from the CW laser diode output itself, i.e. it is a positive feedback mechanism. The output from the back facet of the laser diode is focused on a fast photodetector which generates an RF spectrum corresponding to the intensity noise of the laser. This broadband RF signal is amplified by a wideband preamplifier, and the desired signal for gain-switching is selected from

this broad spectrum by a narrow bandpass RF filter. The filtered signal is passed through a power amplifier and applied to the semiconductor laser via a bias tee. An electrical delay line is include in the feedback path to adjust the phase of this RF modulating signal at the semiconductor laser. At turn-on, the laser diode operates essentially CW with a broad intensity noise spectrum from DC to several GHz. The filter selects a narrow band of frequencies centered at the desired pulse repetition rate f_R, which after amplification results in RF modulation at frequency f_R of the drive current to the laser diode. Since the modulation is derived from the output pulse whose period is fixed by a passive element (the narrow bandpass filter), this scheme has higher phase stability than the modulation derived from an independent and external 'active' source, i.e. a frequency oscillator. Thus this 'filtered feedback' gives rise to the excellent stability of short pulse generation. In addition, variation of the repetition rate is easily accomplished by tuning the center frequency of the bandpass filter.

We note that the method and results described here are considerably different than those reported previously by Paoli and Ripper[1] and by Lau and Yariv[2], where a self-pulsing laser diode was stabilized by optical, optoelectronic or RF feedback techniques. Because this previous work was based on pre-existing self-pulsation in the laser diode (which were locked or stabilized by the feedback loop), the repetition rates obtainable by those techniques were limited to relatively high frequencies (>1 GHz). Moreover, this earlier work required carefully selected laser diodes (to achieve self-pulsation) which were subsequently short-lived because of the existence of intrinsic defects. In contrast, the regenerative gain-switching technique reported here results in picosecond pulse generation from any standard CW laser diode having sufficient modulation bandwidth, and the repetition rates should be tunable over a very broad range of frequencies from near DC to many GHz by appropriate choice or tuning of standard optoelectronic components (primarily RF filters and bias tees).

Regenerative Mode-Locking (RML)

Although semiconductor lasers have been mode-locked by passive, synchronous pumping, hybrid and colliding pulse techniques, the technique of the active mode-locking is the one that is most frequently used to generate picosecond pulses. In active mode-locking, the period of the active modulation is adjusted to precisely match the transit time of the external cavity. A slight detuning between the modulation frequency and the cavity transit time results in a phase shift between the modulation and the mode-locked pulse train, which leads to instabilities in the mode-locking process, degrading both the pulsewidth and the stability of the output. Hence, both a well stabilized laser cavity and a highly stable RF signal generator are required for

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conventional active mode-locking of semiconductor lasers. In our work on regenerative mode-locking, the undesirable phase shift between the modulation and the mode-locked pulse train is automatically eliminated, allowing highly stable active mode-locking of semiconductor lasers without the need for an ultrastable RF signal source or active cavity stabilization.

Figure 2 shows the schematic of the RML technique employing a diode laser. The diode laser (with an AR coating on one facet) is incorporated in an external cavity with a grating reflector (for wavelength tunability). The laser light exiting the rear facet is focused onto a fast photodetector after passing through an optical delay line (for fine tuning of phase shifts). The RF output of the photodetector, corresponding to the fundamental beat note of the longitudinal modes of the external cavity is then selectively amplified, and superimposed on a constant DC bias using a bias tee. Since the modulation in this case (unlike external active mode-locking) is derived from the beating of the longitudinal modes of the optical cavity, changes in this cavity length (e.g. due to the mechanical or thermal variations, etc.) are automatically tracked by corresponding modulation changes for the mode-locking. Therefore perfect synchronism is maintained at all times between the optical cavity and the electrical modulation, even when cavity length changes occur due to mechanical adjustment of the wavelength-tuning elements.

Technical results

Several commercial and CHTM-fabricated semiconductor diode lasers have been gain-switched using the RGS technique. Pulsewidths as short as 35 ps were easily obtained. The amplitudes of these pulses could be varied by varying the DC bias level and the regenerative loop gain until the onset of satellite pulses. Preliminary measurements also indicated moderately good amplitude and phase stability of the pulse train, and the pulse repetition rate was easily tuned from 240 to 430 MHz in a highly controllable manner by incorporating a tunable RF bandpass filter. This tuning range was limited only by the choice of components that were readily available for these preliminary experiments. With the use of relatively standard components, we expect to be able to tune the pulse repetition rate continuously from less than 100 Hz to over 1 GHz with any laser diode having sufficient modulation bandwidth. Using this method, we have been able to observe pulsewidths from 35 ps to 65 ps using several different semiconductor diode lasers at discrete wavelengths between 780 nm and 950 nm. Generation of wavelength tunable pulses should also be possible by incorporating a wavelength tunable laser diode in the arrangement depicted in Figure 1.

Many commercially available semiconductor laser diodes have been mode-locked using the regenerative mode-locking technique. With the use of a Hitachi laser diode in an external cavity of 30 cm length, the center frequency of the RF filter was set at 500 MHz which was the inverse of the cavity transit time. The RF output of the photodetector in the optoelectronic feedback loop was selectively amplified by 60 dB within a 10 MHz bandwidth around the filter center frequency, and phase shifted before applying to the laser diode. When the dc bias of the laser diode was initially adjusted to slightly above threshold, the laser mode locked, emitting a stable train of pulses of ~ 10ps duration. After this onset of mode locking, the dc bias could be lowered

to below the initial threshold level, and the laser still continued to mode lock. Noticeable satellite pulses appeared when the dc bias level was significantly higher than the threshold value. Peak powers of the mode-locked pulses were over 100 mW.

Special comments

We have started discussions with New Focus Inc. on the commercialization of this technology. This would involve development of the various electronic modules used in the feedback loop for broadband operation covering the KHz - MHz range.

Further research

Further work on this project will focus on the following three specific areas :

1) Timing jitter (phase noise) in short pulse diode lasers using regenerative feedback
2) Widely repetition rate tunable (KHz to GHz) regeneratively gain-switched diode lasers
3) Mode-locked diode lasers using anti-resonant Fabry-Perot saturable absorber

1) In short-pulse diode lasers using RF-oscillators for modulation, the pulse-to-pulse rms timing jitter is typically _ 1 ps, by using ultra-stable RF-oscillators with very low phase noise. As described previously, the use of regenerative feedback eliminates the need for highly stable RF-oscillators for supplying the gain modulation or the active modulation, in gain-switched and mode-locked diode lasers, respectively. Since the 'synchronizing' element in these regenerative schemes is the passive bandpass filter, it is expected that they will also exhibit very low phase noise. We are investigating the phase noise characteristics of the regeneratively gain-switched (RGS) and the regeneratively mode-locked (RML) diode lasers. This is being achieved by studying the noise content of the fundamental and successive harmonic sidebands using a high-speed photodetector and spectrum analyzer.

2) Depending on the particular application, picosecond optical pulses are desired with repetition rates from kHz (for optical triggering of high-voltage switches) to GHz (for optical clocking of circuits). The regenerative gain-switched diode laser output builds up by selecting a single frequency (using the bandpass filter) for the optoelectronic feedback, from the 'white noise' like amplitude noise spectrum of its spontaneous emission, and therefore this scheme should be applicable from kHz to GHz repetition rates. For the kHz repetition rate tunable RGS laser, we are implementing the pre-amplifier and power amplifier using low noise audio frequency amplifiers. The tunable bandpass filter is being implemented by a 4th order active filter design (using OP AMPs). The critical element is the nonlinear pulse steepening element in the feedback circuit, since it will determine the pulsewidth of the generated optical pulse. Various designs based on nonresonant comb generators are being tested. For GHz repetition rates, the laser diode should have a large modulation bandwidth (i.e., a sufficiently high relaxation oscillation frequency), which will determine the upper limit of the repetition rate.

3) Compact passively mode-locked diode lasers can be implemented using semiconductor saturable absorbers in an external cavity. Unfortunately semiconductor materials tend to have high absorption cross-sections and hence low saturation intensities. Therefore for higher power operation it is necessary to embed the saturable absorber inside an anti-resonant Fabry-Perot cavity, thus reducing the intensity inside the saturable absorber, while allowing higher intensities in the main cavity. We have designed an antiresonant Fabry-Perot saturable absorber grown epitaxially by MBE in the GaAs/AlGaAs material system. The bottom Bragg mirror has a reflectivity of R~99%, and the top dielectric mirror has R~98%. The saturable absorber is a multi-quantum-well structure, with an n=1 absorption edge at l=0.85 μm. The MQWs are grown at reduced temperatures(~ 350 C) to reduce the carrier lifetimes, and hence act as relatively fast saturable absorbers.

Conference presentations & publications under this ARPA Contract

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